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A Multigrasp Hand Prosthesis for Providing Precision and Conformal Grasps

Daniel A. Bennett [Student Member, IEEE],

Department of Mechanical Engineering, Vanderbilt University, Nashville, TN 37235 USA

Skyler A. Dalley [Member, IEEE],

Vanderbilt University, and is currently with Parker Hannifin Corp., Division of Human Motion and Control, Cleveland, OH 44124 USA

Don Truex, and

Department of Mechanical Engineering, Vanderbilt University, Nashville, TN 37235 USA

Michael Goldfarb [Member, IEEE]

Department of Mechanical Engineering, Vanderbilt University, Nashville, TN 37235 USA

Daniel A. Bennett: daniel.a.bennett@Vanderbilt.Edu; Skyler A. Dalley: skyler.a.dalley@vanderbilt.edu; Don Truex: don.truex@vanderbilt.edu; Michael Goldfarb: michael.goldfarb@vanderbilt.edu

Abstract

This paper presents the design of an anthropomorphic prosthetic hand that incorporates four motor units in a unique configuration to explicitly provide both precision and conformal grasp capability. The paper describes the design of the hand prosthesis, and additionally describes the design of an embedded control system located in the palm of the hand that enables self-contained control of hand movement. Following the design description, the paper provides experimental characterizations of hand performance, including digit force capability, bandwidth of digit movement, physical properties such as size and mass, and electrical power measurements during activities of daily living.

Index Terms

Hand prosthesis; multigrasp prosthesis; robotic hand; terminal device

I. Introduction

Upper extremity prosthetic terminal devices have traditionally been limited to a single degree of freedom (DOF). In contrast, the human hand has approximately 20 DOFs, and can perform a variety of grasps and postures. Recent advances in mechatronics technology

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Contact michael.goldfarb@vanderbilt.edu for further questions about this work.

This paper has supplementary downloadable material available at <http://ieeexplore.ieee.org> provided by the authors. The material is a video of the multigrasp hand prosthesis. The video demonstrates the movement associated with each of the four degrees-of-actuation, and also demonstrates several different precision and conformal grasp types. The size of the video is 7.0 MB and it can be viewed with an MP4 player.

enable the development of multigrasp hand prostheses, which contain multiple actuated DOF and can provide to the user a variety of grasps and postures. Presumably, such “multigrasp” prostheses could offer enhanced functionality to upper extremity amputees. Descriptions of several recently developed multigrasp hands are provided in [1]–[13]. These hands contain between one and six independent actuators and between 8 and 16 joints, where in each device, the discrepancy between the number of actuators and the number of joints is accommodated by differential, kinematic, or compliant coupling. The configuration of each of these hands (i.e., the number and allocation of DOFs, number and allocation of actuators, and type and extent of coupling), as described in [14], varies considerably. Specifically, the manner in which to allocate and configure the DOFs, actuators, and coupling in a multigrasp prosthesis is highly variable, and is highly dependent upon the functional objectives of the hand and the nature of the user interface that controls it.

The authors have previously described and characterized the design of a multigrasp hand prosthesis that contained 16 DOFs actuated by four actuators [10]. Based on experience with that prosthesis, the authors present here a new configuration for a multigrasp hand prosthesis that provides several advantages with respect to the former, as discussed subsequently. To the authors’ knowledge, the configuration presented here has not been previously presented in the engineering literature. This paper describes the new hand configuration, the design embodiment of this configuration and the embedded system that controls it, and presents an experimental characterization of hand performance and functionality. A video is also included in the supplemental material that demonstrates operation of the self-contained prosthesis.

II. Performance and Functional Objectives

A. Grasps and Postures

The design objectives for the hand described in this paper are similar to those previously presented by the authors [10], which are briefly restated here for completeness. Grasps can be grossly classified as either precision or conformal types. The most common precision grasps are the tip, tripod, and lateral pinch grasps, while the most common conformal grasps are the hook, spherical, and cylindrical grasps. Note that the purpose of a precision grasp is generally to provide dexterity, while the purpose of a conformal grasp is generally to provide stability. The former generally involve digits I and II, and possibly III, while the latter generally involve all five digits. The former can be generally characterized by single point contact between an object and each digit (typically at the tip of a digit), while the latter are typically characterized by multiple points of contact, or a continuum of contact, between an object and each digit. These six grasps constitute the vast majority of the grasps used by healthy individuals during the activities of daily living (ADLs) [15], [16]. In addition to these six grasps, the ability to point is an important component of interacting with modern technology interfaces, such as keyboards, cell phones, and touchscreens. Finally, a platform posture is also considered an important component of a complete grasp taxonomy [17], and is useful for holding flat objects, in addition to reaching into confined spaces (e.g., a clothing pocket) or donning clothing over the hand and arm.

B. Digit Forces and Speeds

In addition to forming these grasp shapes and hand postures, in order to offer functionality representative of the healthy hand, the digits of the prosthetic hand should be capable of forces and speeds representative of those characteristic of healthy individuals when performing ADLs. As discussed in [10], based on studies presented in [18]–[20], the digits associated with precision grasp (digits I and II: the thumb and forefinger) should be capable of at least 11 N, and ideally up to 25 N; the composite force exerted by digits III–V (the middle, ring, and little fingers) should be at least 14 N; and the digits should be capable of joint angular velocities of at least 4 rad/s, which on average corresponds to a bandwidth of 1.5 Hz over half of the range of motion of each joint.

C. Physical Properties

Surveys of upper extremity amputees indicate the importance of size, weight, and appearance of a prosthetic hand [21]–[24]. A precise specification with regard to weight is difficult to obtain; despite this, the mass of the native limb along with the mass of existing commercially available prosthetic hands can be used together to provide a nominal mass target for a prosthetic hand. According to the study by Clauser *et al.* [25], the mass of the typical human hand is approximately 400 g. Measurements of commercially available prosthetic hands indicate the following: the Otto Bock MyoHand VariPlus Speed (singlegrasp myoelectric hand) has a mass of 460 g; the Touch Bionics i-LIMB Revolution has a mass of 515 g; and the mass of the Bebionic hand is 500 g (where all measurements exclude cosmesis and battery). As such, a nominal mass target of 500 g was adopted as an appropriate target specification for the multigrasp prosthetic hand described here. With regard to size, based on the anthropometry study [26], a 50% male hand is characterized by a breadth and length of 9.0 and 19.3 cm, respectively, which were adopted as the size specification for the hand described here.

D. Power Consumption

A hand prosthesis should be capable of operating for a full day between battery charges. Surveys have shown that a majority of amputees use their prostheses more than 8 h per day; a substantial proportion use them more than 12 h per day [27], [28]; and some amputees use prostheses up to 16 h per day [23]. As such, a battery charge should provide for at least 12 h of use, and ideally 16.

III. Multigrasp Hand Design

A. Allocation of Actuation for Precision and Conformal Grasping

An essential design objective for the hand prosthesis is to provide both precision and conformal grasps. Recall that a distinguishing feature of the latter is the ability to conform to an object being grasped, thus maximizing the area of contact between the hand and object. In the performance of such grasps, one would like the shape of the object to principally determine the configuration of the hand. Conversely, precision grasps are generally used to handle or manipulate objects that are much smaller than the size of the hand. Such grasps are nonconformal (indeed, the notion of conforming to an object much smaller than the hand is not well posed), and therefore the hand must determine its grasp configuration

independently of the object shape. In such cases, underactuation should be avoided. In order to provide such functionality, the prosthesis described here incorporates four independent actuators. Although a multigrasp prosthesis previously presented by the authors also incorporated four independent actuators [10], the allocation of actuation within the hand described here is specified in a unique manner, motivated by providing the aforementioned precision and conformal grasp capabilities. Specifically, in order to facilitate such functionality, the function of the digits were separated into precision and conformal, where digits I and II (i.e., the thumb and forefinger) were assumed to be principally responsible for precision manipulation, while digits III–V were assumed to principally conform to and stabilize objects during whole-hand grasping. As such, digits I and II were designed with three fully actuated DOFs in order to offer full control of precision grasps, while digits III–V were designed in an underactuated configuration, wherein a single actuator actuates six DOFs through a compliantly coupled differential, in order to offer the stability of a conformal grasps. The specific actuation configuration is illustrated in Fig. 1. In particular, one motor unit provides digit I (thumb) palmar ab/adduction in a fully actuated manner at the carpometacarpal (CMC) joint via bidirectional tendon actuation (DOA 1), while another motor unit provides digit I (thumb) flexion/extension in a fully actuated manner at the CMC joint via bidirectional tendon actuation (DOA 2), while the metacarpal phalangeal (MCP) and the proximal interphalangeal (PIP) joints are fused. A third motor unit provides digit II (forefinger) flexion/extension in a fully actuated manner at the MCP joint via bidirectional tendon actuation (DOA 3), while the PIP and distal interphalangeal (DIP) joints of the digit are fused. Finally, a fourth motor unit provides flexion of the MCP and PIP joints of digits III–V with unidirectional tendon actuation via compliantly coupled differential (DOA 4), while the DIP joints of these digits are fused, and wherein extension of the MCP and PIP joints is provided by compliant elements (i.e., torsional springs) in the respective joints. With this combination of motor units and DOFs, the configuration of digits I and II are determined uniquely as commanded by the motor units, while the configuration of digits III–V are determined by a combination of the motor unit command and the nature (i.e., shape) of the object being grasped. As such, digits I and II are principally responsible for providing precision grasp and manipulation of objects small relative to the size of the hand, while digits III–V provide conformal grasp capability, and in essence stabilize the whole-hand grasping of objects roughly the same size as the hand. In this manner, the hand is able to explicitly provide both precision grasp and manipulation, in addition to whole-hand conformal grasp capability.

In order to present the configuration of the hand in a more technically explicit manner, one can define a kinematic mobility (M) of each degree-of-actuation (DOA) by assessing the number of DOFs that remain after the actuator configuration is prescribed. In the case of a fully actuated joint, there is no kinematic mobility of the system once the actuator configuration is determined (i.e., $M = 0$). Thus, the configuration of a system with zero mobility is determined entirely by the configuration of the actuator, while the configuration of a system with mobility greater than zero is determined by a combination of the actuator configuration and the external and internal forces acting on and within the DOA. For the case of systems actuated in a unidirectional manner (e.g., actuated by a unidirectional tendon working against a compliance), the mobility will be different when loaded against the

direction of actuation (M^+) and when loaded along it (M^-). One can define a kinematic controllability as

$$C = 1 - \frac{M}{DOF}. \quad (1)$$

Note that a kinematic controllability of 1 indicates that the actuator has full control in determining the kinematic configuration of the DOA (i.e., the configuration is determined by the actuator, irrespective of external loading), while a kinematic controllability of 0 indicates the actuator has no ability to control or influence the kinematic configuration of the DOA (i.e., the configuration is determined entirely by external loading). Given these definitions, the mobility of the four DOAs of the hand are given by

$$M_1 = M_2 = M_3 = 0, \quad M_4^+ = 5 \text{ and } M_4^- = 6 \quad (2)$$

where M_1 , M_2 , and M_3 are the mobility of the digits I and II DOAs, and M_4^+ and M_4^- are the mobility of the digits III–V DOA in each respective direction of actuation (+ in flexion and – in extension). In terms of kinematic controllability, when actuated in flexion (or palmar abduction for DOA 1), the respective DOAs are characterized by

$$C_1^+ = C_2^+ = C_3^+ = 1 \text{ and } C_4^+ = \frac{1}{6} \quad (3)$$

while when actuated in extension, the respective DOAs are characterized by

$$C_1^- = C_2^- = C_3^- = 1 \text{ and } C_4^- = 0. \quad (4)$$

Thus, the configuration of digits I and II are fully and uniquely determined by the actuator commands when loaded in either flexion or extension. The configuration of digits III–V is determined by the combination of the actuator command and external loading (i.e., the shape of the object being grasped) when loaded against flexion, with the object shape having more relative influence than the actuator command; while the actuator has no control over the configuration of digits III–V when those digits are loaded against extension.

As a point of reference, a previous hand design presented by the authors [10] incorporated the same number of DOAs, but the respective DOAs were characterized by substantially different kinematic controllability. Specifically, the hand was characterized by mobility of each DOA when loaded against flexion of

$$M_1^+ = 0, M_2^+ = M_3^+ = 2, M_4^+ = 8 \quad (5)$$

and when loaded against extension of:

$$M_1^- = 1, M_2^- = M_3^- = 3, M_4^- = 9. \quad (6)$$

These respective mobilities result in kinematic controllability when loaded against flexion of

$$C_1^+ = 1, C_2^+ = C_3^+ = \frac{1}{3}, C_4^+ = \frac{1}{9} \quad (7)$$

and kinematic controllability when loaded against extension of

$$C_1^- = C_2^- = C_3^- = C_4^- = 0. \quad (8)$$

As such, only the palmar abduction of digit I was fully controllable (C_1^+), and only when loaded against palmar abduction. The configuration of each remaining DOA when loaded against flexion was determined by the combination of the respective actuator command and external loading on the digits (i.e., object properties). The influence of the object on the DOA configuration was greater for digits III–V than for digits I and II, but was the primary influence on DOA configuration in all cases. In the case the digits were loaded against extension (or palmar adduction), the actuators had no influence on the kinematic configuration of each DOA. As such, although the hand described in [10] also included four actuators, the relative mobility and controllability between the two prosthesis prototypes are markedly different.

B. Tendon Actuation and Series and Parallel Elasticity

The ability of the hand to provide full kinematic controllability when loaded in either direction, as described in (3) and (4), is provided by incorporating bidirectional (as opposed to unidirectional) tendon actuation in the three respective DOF/DOAs of digits I and II. In addition to offering full kinematic controllability, such actuation provides higher output impedance (i.e., more rigid posture) in the associated digits. Additionally, the bidirectional tendon configuration eliminates the need for parallel springs in the fingers, which are otherwise required to provide extension in the unidirectional tendon configuration. As such, the tendons need not work against the restoring force of the parallel springs, and thus the motor units when used in a bidirectional tendon configuration generate greater maximum fingertip and grasp forces than when used in a unidirectional configuration. Fig. 2(a) shows a representative bidirectional tendon configuration. Specifically, the figure shows a cross section of digit II and its tendon configuration, which is generally representative of the tendon routing in the three bidirectional-tendon fully actuated axes. Note that the bidirectional tendon path lengths must be matched, such that the overall tendon path is constant (i.e., the tendon on the anterior aspect of the joint is configured to remain in contact with the constant-radius joint). In order to eliminate backlash, a linear spring (10.5 N/mm) is located in the fingertip which imposes series elasticity on the extension side of the tendon and maintains a pretension on the bidirectional tendons. Note that, since this spring is in the extension tendon, it has no significant effect on behavior during grasping.

Although bidirectional actuation provides important advantages for the fully actuated (precision grasp) DOFs, unidirectional tendon actuation provides important advantages for the (conformal grasp) underactuated DOA. Most evidently, a unidirectional configuration reduces the total amount of spooled tendon by a factor of 2, which is particularly important given the fact that three digits are being actuated, and thus the total space savings (especially

in the motor unit pulley) is significant. Perhaps more importantly, however, the unidirectional tendon configuration is well suited to enabling conformal grasp via a compliantly coupled mechanical differential. Fig. 2(b) shows a representative cross section of digit III and its tendon configuration, which is generally representative of the tendon routing in the three digits associated with the underactuated DOA. Like the bidirectional tendon configuration, the unidirectional tendon includes a series stiffness in the fingertip; unlike the bidirectional configuration, however, the stiffness is on the flexion side of the digit, and the spring (0.75 N/mm) is configured with a considerably lower stiffness than the preload spring on the bidirectional extension tendon in order to provide a greater degree of displacement. The resultant effect of these springs is to provide a differential coupling between the three conformal digits when loaded against flexion, such that the digits can be differentially displaced in addition to the differential movement between the MCP and PIP joints within each digit. In addition to the tendon series springs, the MCP and PIP joints of the associated digits include torsional springs (40 mNm/rad) within each joint [see Fig. 2(b)] which provide return torques to maintain tendon tension and provide for digit extension, and also provide a parallel stiffness that determines the nature of joint movement in the absence of contact with an object. Note that, regarding the latter, although the torsional springs in the MCP and PIP joints are all of the same stiffness, the radius of the tendon path around the MCP is 30% larger than the radius around the PIP, and as such the MCP will undergo 30% greater flexion than the PIP when moving through free space, in order to provide a cascading pattern of joint movement.

C. Motor Unit Design

Each DOA is actuated by a motor unit consisting of a Faulhaber 1226 brushless DC servomotor, a 64:1 planetary gearhead reduction, a custom two-way clutch unit, and bidirectional or unidirectional tendon pulleys, as per the specific DOA. Each bidirectional tendon pulley consists of a double pulley for the flexion and extension sides of the tendon, respectively, while the unidirectional tendon pulley consists of a triple pulley, one for each of the flexion tendons in digits III–V. The clutch provides high drive efficiency in the forward path, but precludes back drivability, such that the configuration of the hand can be maintained without electrical power consumption. The motor unit design and configuration are shown in Fig. 3. With the exception of the bidirectional pulleys, the motor units are similar to motor unit designs presented in previous publications by the authors [10].

D. Cosmesis and Construction

The primary form of the hand prosthesis consists of two materials: a high-modulus material forms the load-bearing geometric and kinematic structure of the hand, while a low modulus material provides a “soft tissue” covering that provides compliance and shape to facilitate grasping and manipulation of objects. Both materials are produced by additive manufacturing processes. The high modulus material is a thermoplastic with a flexural modulus of approximately 1750 MPa and a flexural strength of approximately 60 MPa (3-D Systems Accura Xtreme), while the low modulus material is an elastomer with a Shore A durometer of 40 (PolyJet Tango Black). The elastomer is slipped on the “skeletal” structure of each digit, and bonded to the anterior and posterior sides of the palm using adhesive.

E. Embedded System Design

An embedded system was developed for the hand in order to enable fully self-contained control of all DOAs of the hand. The embedded system was designed to be powered by a 14 V battery (located elsewhere in the prosthetic arm); to accept and execute motion and/or force commands from a high-level controller via a controller area network (CAN) serial interface; and to return processed position and force information for each DOA to the high-level controller via the CAN bus. The embedded system consists of a single, four-layer circuit board that is fully contained within the palm of the hand prosthesis. The “hand control board” contains four custom brushless motor pulse-width modulation (PWM) servoamplifiers, each operating at a PWM frequency of 20 kHz, and each capable of maximum continuous current of 3.5 A. All four servoamplifiers are controlled by a single microcontroller (Microchip dsPIC33). In addition to the dsPIC, the components on both sides of the board associated with the servoamplifier channels are outlined in Fig. 4. In addition to providing Hall-based brushless motor commutation and servoamplification, the dsPIC also provides closed-loop PID position control of each DOA, with each closed loop running at a sampling rate of 1 kHz. Finally, the hand board sends real-time sensor information regarding tendon excursion (from Hall sensors) and tendon force (via motor current), at a sample rate of 1 kHz, over the CAN bus to the high-level controller. Note that sensing tendon excursion via the Hall sensors at the motor provides a direct measurement of digit configuration for the fully actuated digits I and II, but provides only an average configuration for the underactuated digits III–V (i.e., the single measurement provides the average flexion in the six actuated joints, but cannot distinguish between all sets of configurations corresponding to a given tendon displacement). It should be noted that, even if the system were able to independently sense the configuration of all (six) joints in digits III–V, the only the average flexion is controllable by the single actuator. A block diagram of the functionality of the embedded system is shown in Fig. 5. The location of the embedded system within the palm of the hand is shown in Fig. 6.

IV. Characterization of Hand Performance

A. Hand Size and Mass

The mass of the prosthetic hand, including the embedded system encased in the palm, is 546 g. The major dimensions of the hand are 8.9 cm across the widest portion of the palm, and 20 cm from the base of the palm to the tip of digit III. Based on anthropometric norms as given in [26], these dimensions correspond to the breadth and length of a 35th percentile and 85th percentile male hand, respectively. Note that while the breadth is constrained by the layout of the palm, the length of the hand is not as substantially constrained, and could be shortened without difficulty by decreasing the length of the fingers. Shortening the finger length by 1 cm, which is well within the dimensional constraints of the finger design, would render the overall dimensions equivalent to that of a 35th percentile male (9 cm breadth, 19 cm length). The hand dimensioned as such would further correspond to a hand breadth and length of a 99th and 85th percentile female hand, respectively.

B. Fingertip Forces

Fingertip forces were measured by applying 2.5 A of current to the motor unit for a duration of 1 s. Note that each motor unit incorporates a two-way clutch, and as such it is presumed that sustained grasping would be performed passively, first by squeezing the object for a short period (e.g., 1 s), then turning off the motor current and allowing the combination of the series elasticity and two-way clutches to passively hold the respective grasp force. An Exttech Instruments 475044 force gauge was attached orthogonally to the fingertip to measure the resulting fingertip force. Three trials were taken at four different tendon excursions, spaced evenly at 0, 25%, 50%, and 75% excursion of the tendon, and the average force for each tendon excursion recorded. For digits III–V, the force gauge was attached to all three fingers at once, and the combined force provided by the three fingers was measured together. Fig. 7 shows the maximum fingertip force data corresponding to these measurements. Specifically, the two direct-drive DOAs corresponding to flexion of digits I and II are each capable of maximum fingertip forces between 25 and 30 N, depending on tendon excursion. Note that variation in fingertip forces in these DOAs may be due to variation in frictional characteristics of the joints and tendon paths, and may also reflect variation in the actuator pulley diameter due to tendon spooling onto the pulley at increasing tendon excursions. For a typical tip grasp, digit I (i.e., the thumb) remains nearly extended (approximately 0% tendon excursion), while digit II (i.e., the index finger) becomes almost fully flexed (~80% tendon excursion), such that the maximum tip grasp force is estimated to be approximately 29 N. The combined efforts of digits III–V provide grasp forces between 16 and 23 N, depending on tendon excursion. Assuming a nominal tendon excursion of 50%, the maximum fingertip grip strength of the hand, obtained by combining the fingertip forces of digits II–V, is approximately 45 N. The grip forces are obviously greater if contact with a given object occurs proximal to the fingertips. Note that the grasp forces provided by the prosthesis are well within the ranges typically required by ADLs, as previously discussed.

C. Motion Bandwidth

The motion bandwidth of the fingers was measured during unloaded movement, wherein each motor was driven with a sinusoidal position command, at an amplitude of half of the total tendon excursion, with the center point of oscillation corresponding to the center of the range of motion. As discussed previously, the embedded system provides PID servocontrol of each motor unit, and as such the movement bandwidth was assessed by recording the relative magnitudes of the commanded and measured tendon movement. The results for each of the motors units are shown in Fig. 8. Note that the direct drive DOAs each have a –3 dB bandwidth of approximately 6 Hz, while the underactuated (unidirectional) DOA exhibits a –3 dB bandwidth of approximately 3 Hz. Note that both are well above the 1.5 Hz bandwidth that nominally characterizes ADLs, as previously discussed.

D. Hand Postures and Grasps

Fig. 9 shows the ability of the assembled hand prototype to achieve the aforementioned eight grasps and postures under motor control. A video is included in the supplemental material that dynamically demonstrates these grasps and postures. A method by which the hand can

be controlled by the user to provide these postures and grasps via a standard two-site myoelectric interface is described in [29].

E. Battery Life

The electrical power required by the hand was characterized by assessing the electrical power consumed by the two basic activities performed by the hand, which are movement and grasping. With regard to movement, electrical power is required to move from one hand posture or grasp configuration to another. With regard to grasping, electrical power is required to form and to release a grasp, although the presence of the two-way clutches renders the power consumption independent of grasp duration. Specifically, power is required to achieve a given grasp force, but once achieved, the clutches “lock in” the grasp, such that electrical power is no longer required. As such, the electrical power requirements of the hand were characterized by two assessments. First, in order to characterize the power required to perform movements, the amount of electrical power required to move between a canonical set of postures was measured. Specifically, the electrical power was measured starting in the cylindrical (or power) grasp and moving to the tip, platform, point, hook, and lateral pinch grasps, then reversing the sequence back to the cylindrical grasp. Note that the remaining grasps are subsets of these grasps, but depend on the presence of objects. While this sequence was performed, the current drawn from a 14 V battery by the embedded system in the hand was measured using a current probe (Agilent model 1146A), and the power integrated over the duration of the movement in order to obtain the electrical energy required from the battery to perform this sequence of movements. The measurement was repeated ten times using the previously described sequence, with an average current requirement of $2.18 \text{ A} \cdot \text{s}$, which at the battery voltage of 14 V results in an average energy requirement of 30.5 J (to move through the sequence and back).

The electrical power requirements to grasp and release an object were characterized by grasping a 500 mL water bottle filled to a mass of 500 g (approximately full), grasping with a force sufficient to securely lift the bottle, then releasing the bottle. Like the posture sequence, this activity was performed ten times, with an average current requirement of $2.25 \text{ A} \cdot \text{s}$, and therefore an average energy requirement of 31.5 J, which incidentally was nearly identical to the energy required to perform the posture sequence.

The battery being used in these tests was a 14 V, 1.35 A · h lithium polymer battery, which has a mass of 133 g. As such, the battery provides a gravimetric energy density of 511 J/g. Given this battery (or one of similar gravimetric energy density), the hand could grasp and release a water bottle approximately 16 times per gram of battery weight, or could move through the full suite of hand postures approximately 17 times per gram of battery weight. For the 133 g battery used in the hand prosthesis prototype, the hand could perform approximately 2100 power grasps, approximately 2300 movement sequences, or perform some combination of these activities, on a single battery charge.

V. Conclusion

The authors describe here a hand prosthesis that incorporates a unique configuration of four actuators to explicitly provide both precision and conformal grasp capability. The authors

describe the actuation configuration of the hand in terms of kinematic controllability. A performance characterization indicates the hand prosthesis provides levels of force and speed appropriate for performing the ADLs. The physical properties of the hand are additionally representative of the size and mass of a typical male hand. Electrical power measurements indicate that the prosthesis is able to provide over 1600 grasps or movement sequences on one charge of a 100 g battery. The authors believe that the composite grasp capability and biomechanically representative performance characteristics of such technology have considerable potential to enhance the functionality and thus improve quality of life of upper extremity amputees.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Biographies

Daniel A. Bennett (S'11) received the B.S. and M.S. degrees in mechanical engineering from Case Western Reserve University, Cleveland, OH, USA, in 2009 and 2010, respectively. He is currently working toward the Ph.D. degree in the Department of Mechanical Engineering, Vanderbilt University, Nashville, TN, USA, where he is a Research Assistant in the Center for Intelligent Mechatronics.

His research interests include the design and control of biomimetic robotic devices, specifically, the development of upper extremity prosthetic devices.

Skyler A. Dalley (M'09) received the B.E. and Ph.D. degrees in mechanical engineering from Vanderbilt University, Nashville, TN, USA, in 2007 and 2013, respectively.

He is currently a Principal R&D Engineer with Parker Hannifin Corporation, Cleveland, OH, USA, in the division of Human Motion and Control. His research and development interests include the design and control of electromechanical devices for medical applications and, in particular, the development of prosthetic and orthotic devices for the extremities and spine.

Don Truex received the B.S. degree in electrical engineering from Tennessee Technological University, Cookeville, TN, USA, in 1992.

Since then, he has specialized in the design of embedded system hardware and firmware. He joined the Department of Mechanical Engineering, Vanderbilt University, Nashville, TN, in 2009, as a Research Engineer. His research interests include the design of electronic hardware and firmware for the servo control of brushless dc motors, specifically for use in robotic prosthetics.

Michael Goldfarb (S'93–M'95) received the B.S. degree in mechanical engineering from the University of Arizona, Tucson, AZ, USA, in 1988, and the S.M. and Ph.D. degrees in mechanical engineering from Massachusetts Institute of Technology, Cambridge, MA, USA, in 1992 and 1994, respectively.

Since 1994, he has been with Vanderbilt University, Nashville, TN, USA, where he is currently the H. Fort Flowers Professor of Mechanical Engineering, Professor of electrical engineering, and Professor of physical medicine and rehabilitation. His technical specialization is in the design and control of robotic systems that interact physically with people, and his primary research interest is to apply this specialization toward the development of assistive devices to improve quality of life for people with physical disabilities. Recent work includes the development of multigrasp upper extremity prostheses, powered lower extremity prostheses, and powered lower limb orthoses for individuals with mobility deficits.

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Fig. 1.
Allocation of actuation in hand prosthesis.

Fig. 2.
Cross-sectional view of (a) digit II and (b) digit III.

Fig. 3.
Exploded view of motor unit, including clutch and pulley.

Fig. 4.
Top and bottom views of hand embedded system.

Fig. 5.
Hand board embedded system architecture.

Fig. 6.
Hand with cover removed, showing embedded system and motor units.

Fig. 7.
Fingertip forces corresponding to each motor unit.

Fig. 8.
Bandwidth corresponding to each motor unit.

Fig. 9.
Canonical grasps and postures provided by the hand prosthesis.